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Finite Element Analysis of the Arquin-Designed CMU Wall under a Dynamic (Blast) Load

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Abstract

The Arquin Corporation designed a CMU (concrete masonry unit) wall construction and reinforcement technique that includes steel wire and polymer spacers that is intended to facilitate a faster and stronger wall construction. Since the construction method for an Arquin-designed wall is different from current wall construction practices, finite element computer analyses were performed to estimate the ability of the wall to withstand a hypothetical dynamic load, similar to that of a blast from a nearby explosion. The response of the Arquin wall was compared to the response of an idealized standard masonry wall exposed to the same dynamic load. Results from the simulations show that the Arquin wall deformed less than the idealized standard wall under such loading conditions. As part of a different effort, Sandia National Laboratories also looked at the relative static response of the Arquin wall, results that are summarized in a separate SAND Report.

Acknowledgments

The authors would like to thank the Small Business Assistance Program for supporting this collaboration between Sandia National Laboratories and the Arquin Corporation. The authors would also like to thank Douglas J. Ammerman, Richard P. Jensen, and Clifford K. Ho from Sandia National Laboratories for their review and helpful comments on this report. The work described in this report was funded through the New Mexico Small Business Assistance initiative at Sandia National Laboratories. Neither Sandia nor the U.S. Government acquired any rights in any Arquin Corporation intellectual property as a result of this work.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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Introduction

The Arquin Corporation designed a CMU (concrete masonry unit) wall construction and reinforcement technique that includes the use of steel wire and polymer spacers. The resulting continuous ties are laid on top of each row of the wall as shown in Figure 1. The spacers provide accurate spacing and alignment for each CMU that is laid on top and the assembled ties are also intended to provide additional structural integrity when laid in between each row of the wall (see Figure 2).

In the past, The Arquin Corporation contacted Sandia National Laboratories' Small Business Assistance Program to obtain technical assistance in the following areas:

1. Identification of suitable plastic materials and designs for spacers for optimal performance and lowest cost.
2. Evaluation of enhanced structural integrity of walls with ties.

The findings of the work performed in these areas are summarized in Ho et al. (2008, SAND2008-5518). In the previous work, all the analyses were performed with a static analysis solver. Most recently, the Arquin Corporation was able to obtain more technical assistance from Sandia's Small Business Assistance Program to evaluate the effect of dynamic loading on this different wall design. This report summarizes the results from the dynamic analysis of a blast-like load applied to the Arquin wall design and compares the performance of the Arquin wall with that of an idealized standard wall exposed to the same dynamic loading.

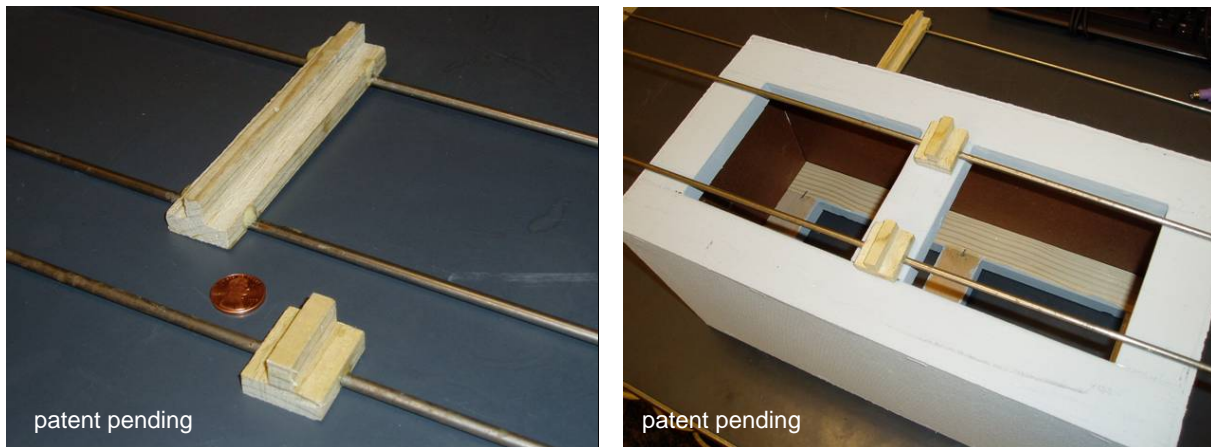


Figure 1. Left: Prototype designs made of wood for the Arquin spacer. Right: Filaments (ties) comprised of the spacers and 9-gage steel wires are laid on top of a CMU. (From Ho et al., 2008)

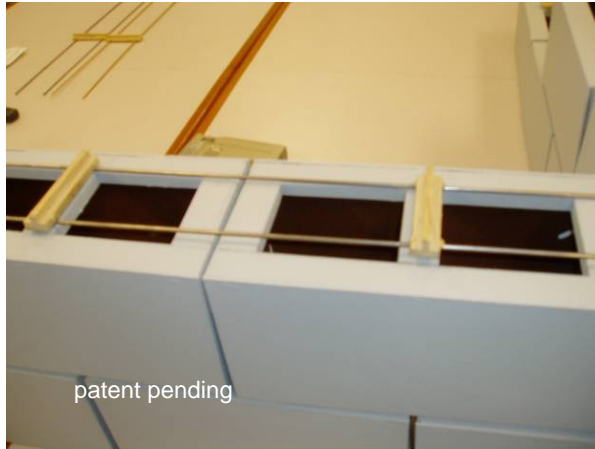


Figure 2. Left: Filaments of ties provide spacing and alignment for rows of CMUs. Right: Assembly of CMUs and filaments. (From Ho et al., 2008)

Geometry and Modeling

The CMU wall examined here has overall dimensions of approximately 8 feet long by 4 feet high by 8 inches thick. Each CMU is approximately 16 inches by 8 inches by 8 inches. The horizontal and vertical mortar lines are both $3/8$ inches thick. The full wall has 6 rows of CMU with 6 CMUs across in an offset pattern.

Computer Model

Figure 3 shows the finite element model of the wall. Since the full wall is symmetric about the vertical centerline and is uniformly loaded, only one-half is modeled. Finite elements in this model are approximately 1 inch in size, which allows for 8 elements through-the-thickness of the wall. Figure 3 also shows the CMUs with the mortar and concrete fill removed from the image. In this study, two different wall configurations are considered. These two walls are designated as the “Arquin wall” and the “idealized standard wall.”

Figure 4 shows the location of the concrete fill for the Arquin wall. Here, concrete is assumed to be poured down the open cells of the concrete blocks to form vertical columns. Figure 4 also shows the location of a weak fill material used in the modeling of the wall. In real construction, these regions may be void, but are modeled here as a weak fill material to avoid potential computer modeling issues. This weak fill material does not contribute any significant strength to the wall.

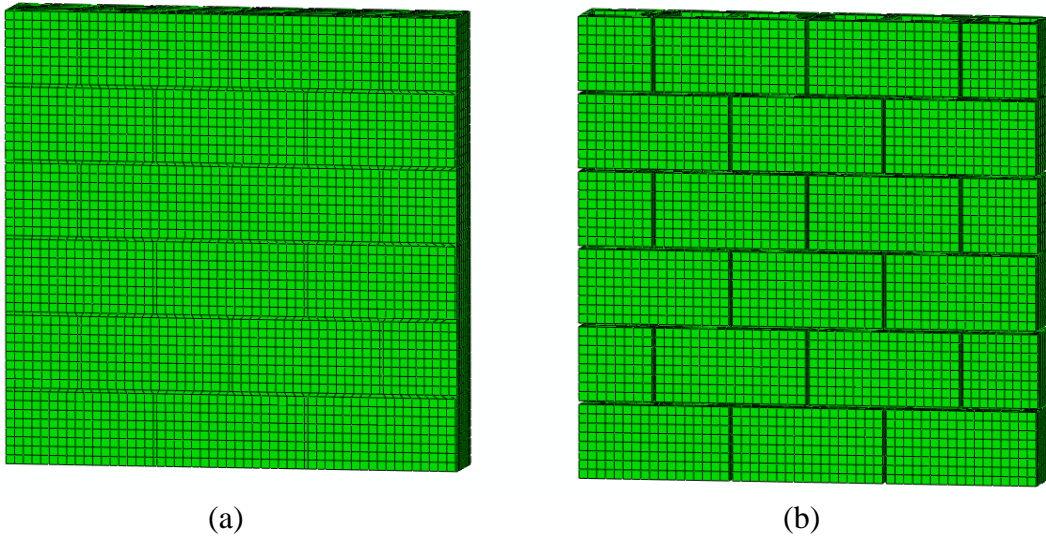


Figure 3. Finite element model of CMU wall; (a) CMUs with the mortar and concrete fill and (b) CMUs only

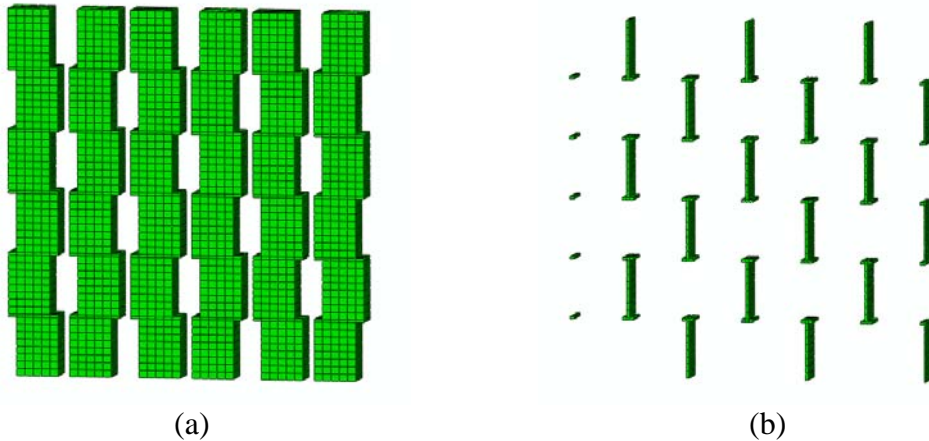


Figure 4. (a) Concrete fill and (b) weak fill material locations for the Arquin wall

Figure 5 shows the location of the concrete fill and weak fill material for the idealized standard wall. The idealized standard wall is assumed to only have concrete fill in every third vertical cell. Therefore, the weak fill material is used in the remaining cells. Again, the weak fill material is assumed to not contribute significantly to the strength of the wall. Figure 6 shows the layout of the mortar for both walls. The mortar is assumed to be applied to the faces of each wall and penetrate 1-5/8 inches from each face.

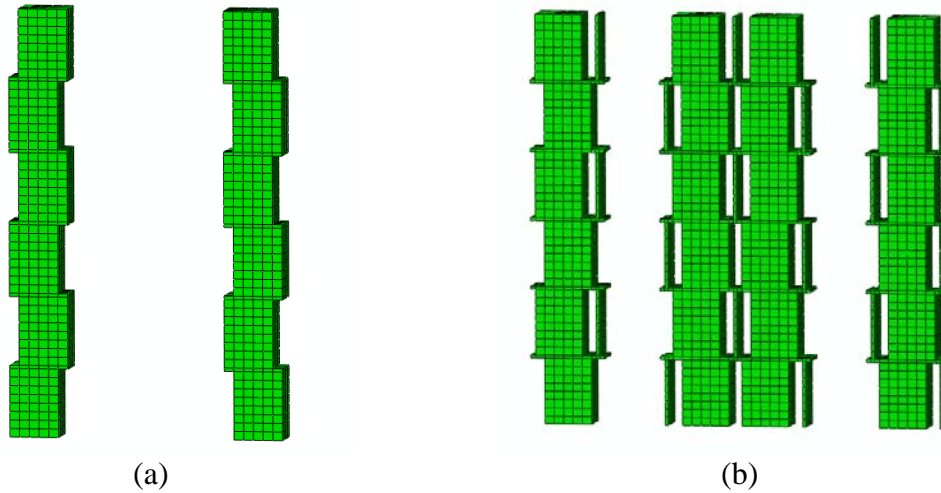


Figure 5. (a) Concrete fill and (b) weak fill material locations for the idealized standard wall

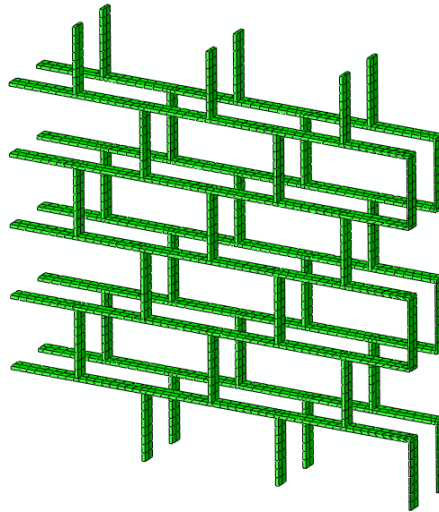


Figure 6. Mortar location for both the Arquin and the idealized standard wall

Figures 7 and 8 show the locations of the reinforcement used in the Arquin wall and the idealized standard wall, respectively. The Arquin wall has vertical rebar spaced in every third cell (a total of two rebar for one-half the length of the wall). Each vertical rebar is a #3 bar with an area of 0.11 in^2 (diameter of $3/8$ inch). It also has 5 filaments, one in each horizontal mortar line, centered through the thickness (note that this is different than what is shown in Figures 1 and 2). Each filament is a 6 gauge wire with an area of 0.0206 in^2 (diameter of 0.16 inch). The size and location of the vertical rebar for the idealized standard wall is identical to the Arquin wall. However, in the horizontal direction, the one rebar used is also a #3 bar with an area of 0.11 in^2 (diameter of $3/8$ inch) and is placed in the horizontal mortar line at the mid-height. The five Arquin filaments have approximately the same area of reinforcing as one #3 bar.

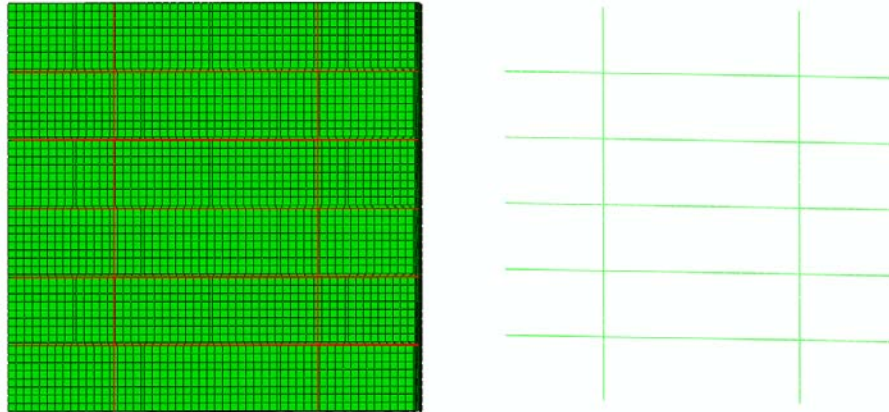


Figure 7. Arquin wall finite element model – Two vertical rebar and five horizontal filaments

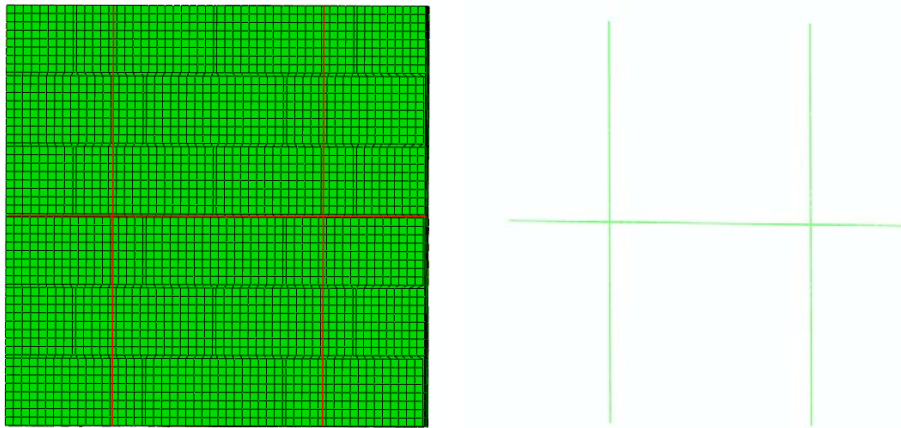


Figure 8. Idealized standard wall finite element model – Two vertical rebar and one horizontal rebar

Boundary Conditions and Loading

The wall is modeled with the bottom fixed against displacement and rotation. In other words, the bottom is essentially “cast in concrete”. Figure 9 shows this region along the bottom. The displacement of the left side of the wall is restricted against motion in the out-of-plane direction. This region is shown in Figure 10 and can be imagined as the left side of the wall being placed next to a strong column. Rotation of the end of the wall is allowed, as is displacement in the plane of the wall.

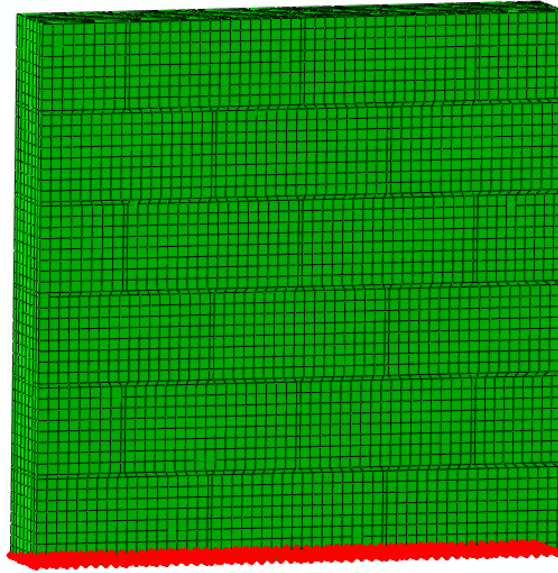


Figure 9. CMU wall finite element model – fixed bottom region (red markers)

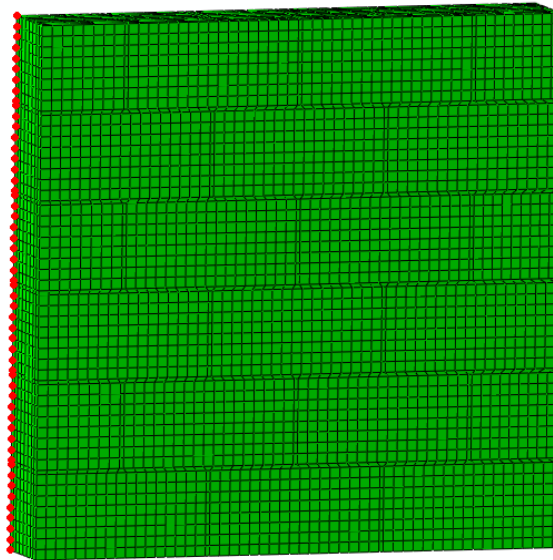


Figure 10. CMU wall finite element model – region of restricted out-of-plane motion (red markers)

Since only one-half of the wall is modeled, symmetry conditions are imposed on the right side of the model (region shown in Figure 11). The finite element analysis of the wall treats this as if the wall is identical, or mirrored, on the other side of this plane.

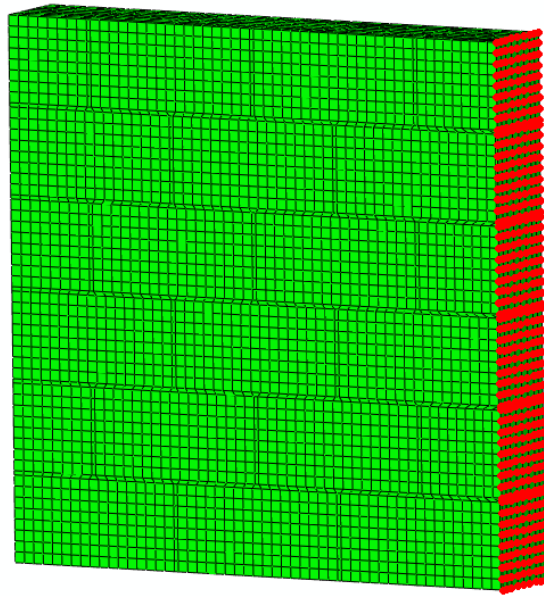


Figure 11. CMU wall finite element model – symmetry plane boundary condition (red markers)

Figure 12 shows the region where a pressure load is applied to the wall. During the analysis, a pressure pulse is applied to this face of the wall. The applied pressure reached a maximum of 30 psi at 0.01 seconds, then dropped to zero at a time of 0.015 seconds as illustrated in Figure 13.

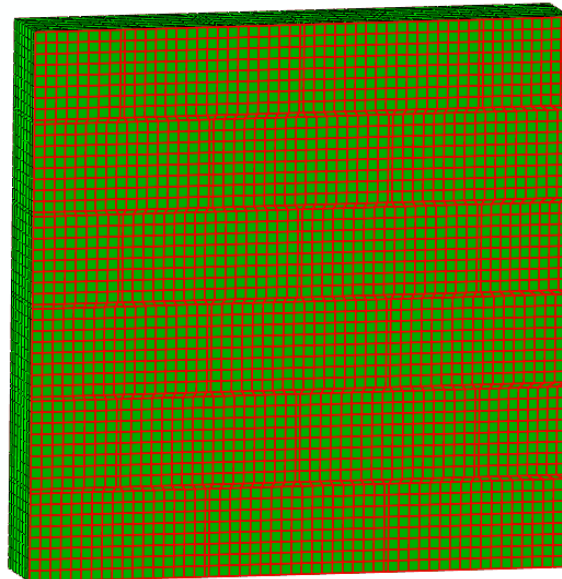


Figure 12. CMU wall finite element model – uniform pressure application region

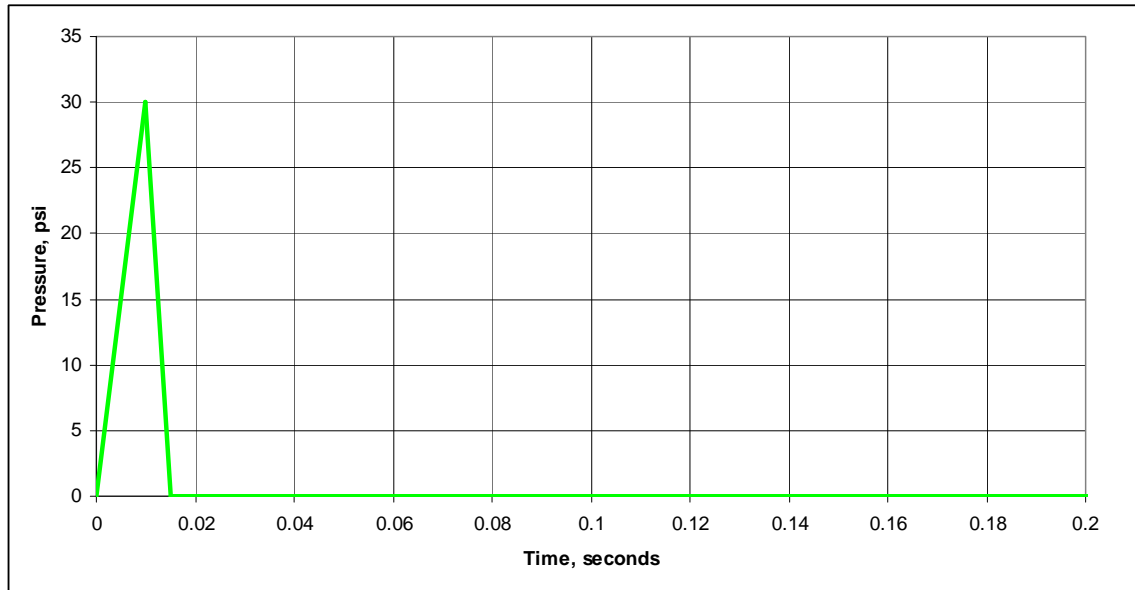


Figure 13. Dynamic pressure load applied to one face of the CMU wall

Material Properties

For the two analyses performed in this study, material properties were assigned to each of the components used in the model. All reinforcing filaments and rebar were modeled as the same steel material with an elastic modulus of 29,000 ksi, a yield strength of 60 ksi, and an ultimate strength of 80 ksi. The concrete material used for the CMUs (Figure 3) has an elastic modulus in both compression and tension of 3372 ksi. The unconfined compressive strength is 3500 psi and the tensile strength is set at 350 psi. The concrete material used for the fill (left side of Figures 4 and 5) has an elastic modulus in both compression and tension of 4188 ksi. The unconfined compressive strength is 5000 psi and the tensile strength is set at 500 psi.

The weak fill material (right side of Figures 4 and 5) has an elastic modulus in both compression and tension of 16 ksi. The unconfined compressive strength is 18 psi and the tensile strength is set at 1 psi. The weak fill material properties are two orders of magnitude smaller than the concrete material used for other parts of the wall model. Therefore, any strength added by the weak fill is assumed to be negligible.

The mortar material (Figure 6) has an elastic modulus in both compression and tension of 1620 ksi. The unconfined compressive strength is 1800 psi and the tensile strength is set at 100 psi. The tensile strength of the mortar is set slightly lower than the 10% of the compressive strength used for the concrete blocks and concrete fill materials. In reality, the tensile strength of the mortar is closer to 10% of the compressive strength (~180 psi). However, the interface (bonding) between the CMU and the mortar will most likely be relatively weak. Therefore, the tensile strength of the mortar was lowered to reflect the reduced tensile strength of this interface.

Analysis Code

The finite element modeling conducted in this study uses the ABAQUS (ABAQUS ver. 6.5) suite of analysis software. Specifically, Version 6.5-6 of the ABAQUS/Explicit general-purpose finite element program and the ABAQUS/CAE interactive environment are used to perform the analyses and to create the solid models and finite element meshes, respectively. ABAQUS/Explicit is employed since all of the analyses performed here are dynamic. The CAE component of ABAQUS provides an interface for defining the model geometry, material properties, boundary conditions, loadings, and meshing.

Simulation Results

The two cases described earlier in this report were analyzed with the pressure pulse loading shown in Figure 13. The maximum displacement in each case occurs at the top of the wall and at the mid-span (top right corner of the symmetric model analyzed as shown in Figure 14). The displacement at the mid-height of the wall at the mid-span was also examined. Figure 15 compares the displacements at the top and mid-height of the wall as a function of time for both the Arquin and the idealized standard wall. Results show that the maximum displacement in the idealized standard wall is approximately 8 inches, leveling off at about 7 inches of permanent deformation. The finite element model used, while numerically accounting for damage in the material, is not capable of simulating material separation. In other words, the model is not capable of showing collapse of the wall. However, the 8 inches of displacement is equal to the original thickness of the wall. This level of displacement most likely signifies collapse of the wall or at least portions of the wall.

For the Arquin wall, the maximum displacement is just over 3 inches, with approximately the same amount of permanent deformation. Figures 16 and 17 also compare the final deformed shape of both walls. These images show that even though the Arquin wall has less displacement, it is severely damaged as well. However, collapse of the wall is not as definitive as is for the idealized standard wall. The difference in the two walls lies in the horizontal reinforcement and in the vertical concrete fill distribution. The five Arquin filaments have approximately the same total area as the one horizontal #3 rebar. Therefore, it is not likely that this causes a significant difference in wall behavior for a distributed load on one face of the wall. The distribution of the concrete fill is the most likely cause for the stiffer behavior in the Arquin wall. The idealized standard wall was modeled with concrete fill in every third cell (location of vertical #3 rebar) as shown on the left side of Figure 5. The Arquin wall included concrete fill in every cell as shown on left side of Figure 4. Since the Arquin wall, as modeled here, contains three times the concrete, it is not surprising that it is stronger. Figures 18 and 19 show the stress distribution on the vertical rebar and horizontal filament at times when maximum stress was observed anywhere on the steel reinforcement. Figure 18 is for the idealized standard wall and Figure 19 is for the Arquin wall.

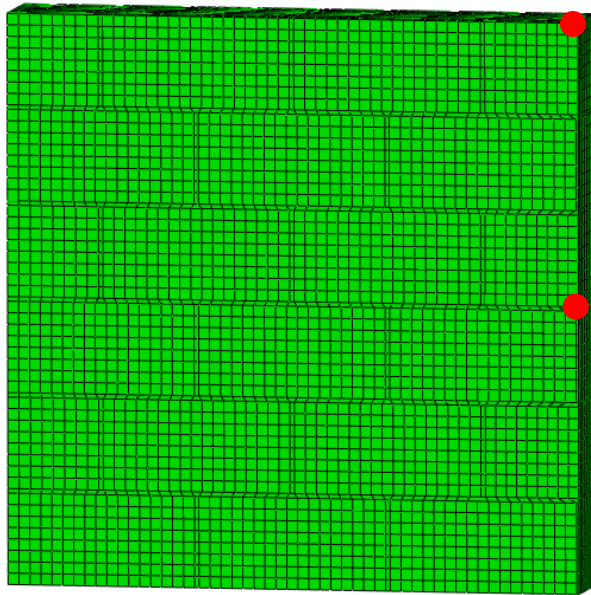


Figure 14. Locations (red markers) used to measure CMU wall displacement

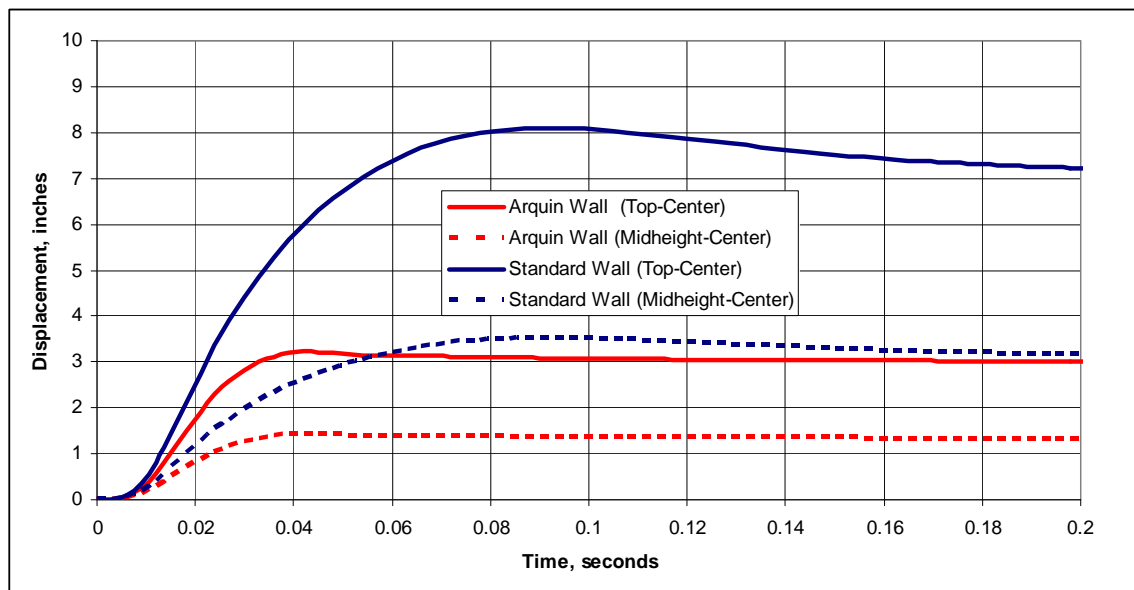


Figure 15. Transient displacement of simulated CMU walls

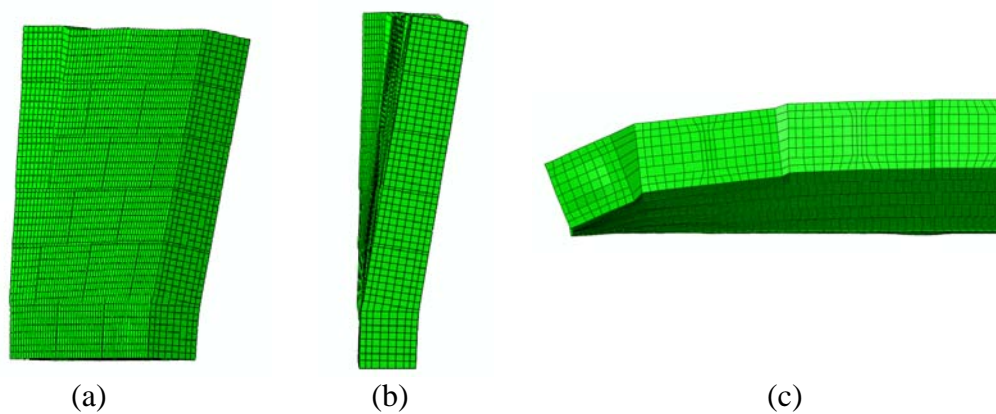


Figure 16. Idealized standard CMU wall displaced shape at times exceeding 0.2 seconds; (a) isometric view, (b) side view, (c) top view

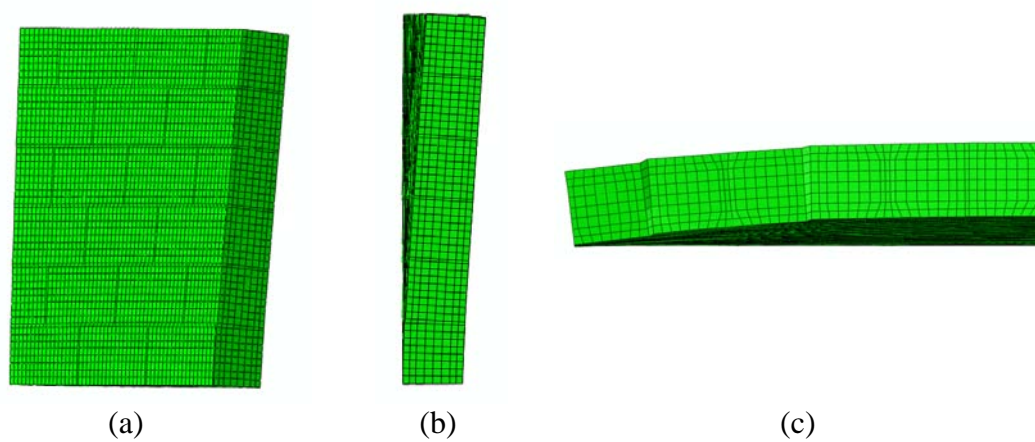


Figure 17. Arquín CMU wall displaced shape at times exceeding 0.1 seconds; (a) isometric view, (b) side view, (c) top view

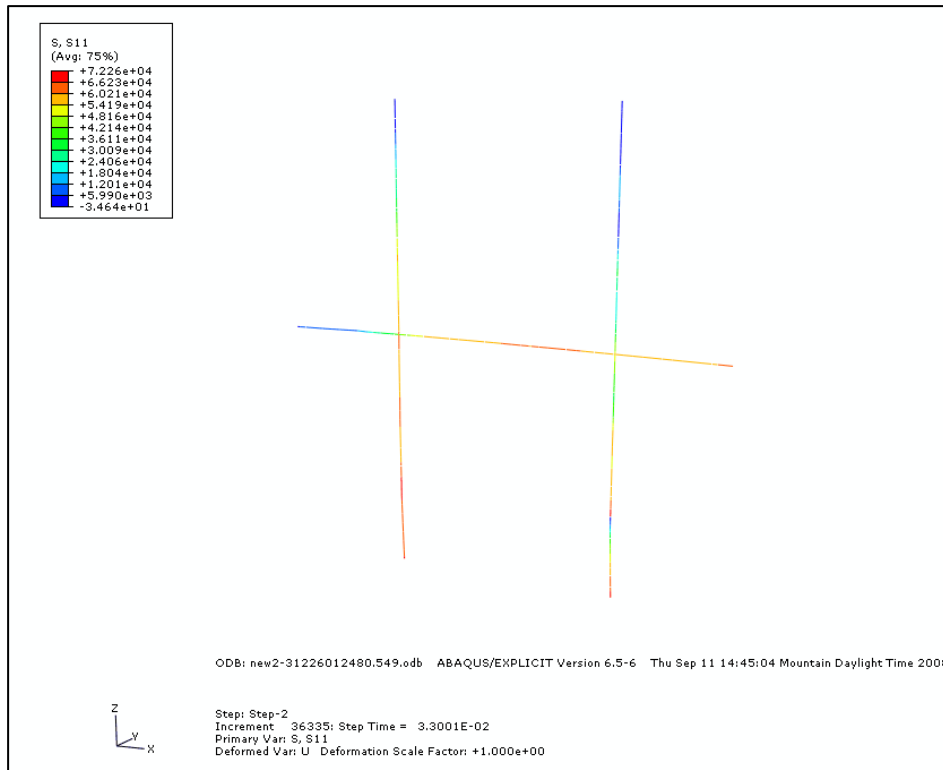


Figure 18. Rebar stress distribution (in psi) – idealized standard wall

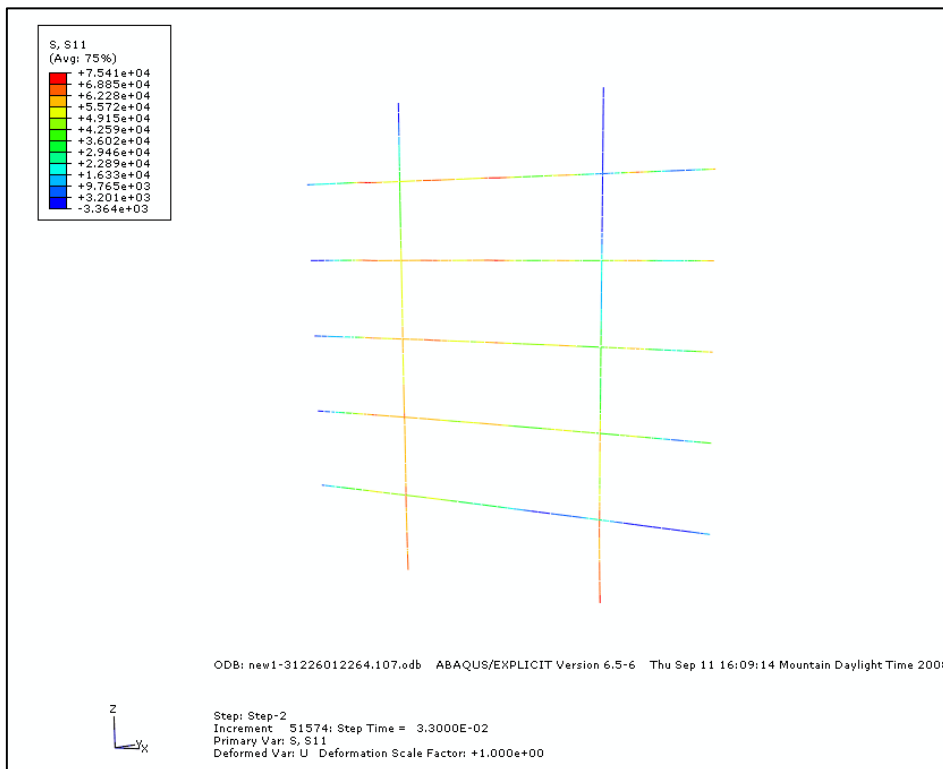


Figure 19. Rebar and wires stress distribution (in psi) - Arquin wall

Special Case Study – Analysis of the Arquin Wall with Fixed Horizontal Filaments

A case exposing the Arquin wall to the same loading described earlier in this report, but with the horizontal filaments and a section of the side of the wall assumed to be fixed is described next. Figure 20 shows the region on the end of the wall where a fixed (no movement) boundary condition was applied. Figure 21 shows the wall displacement for this special case. Fixing the sides of the wall does not allow for significant rotation and result in much lower displacements. However, the analysis does indicate significant cracking throughout. Figure 22 shows the stress distribution on the vertical rebar and horizontal filament at the time when maximum stress was observed anywhere on the steel reinforcement.

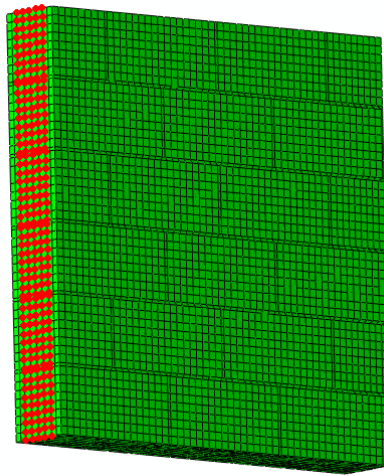


Figure 20. Arquin wall with fixed region (displacements fixed in all directions) identified with red markers

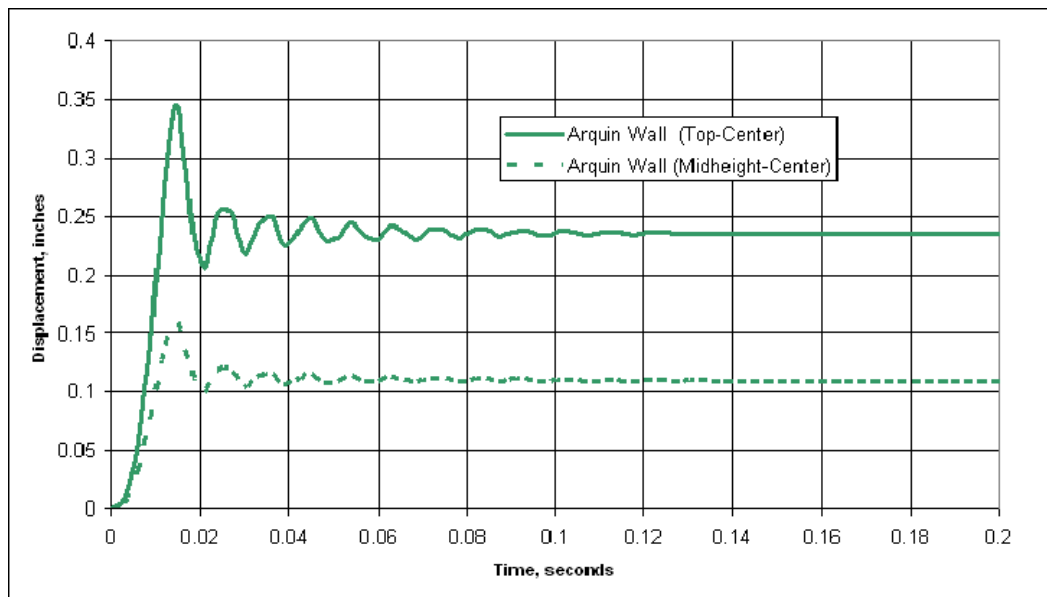


Figure 21. Resulting displacement plot for the fixed Arquin wall exposed to the same loading as the other analyses in this report

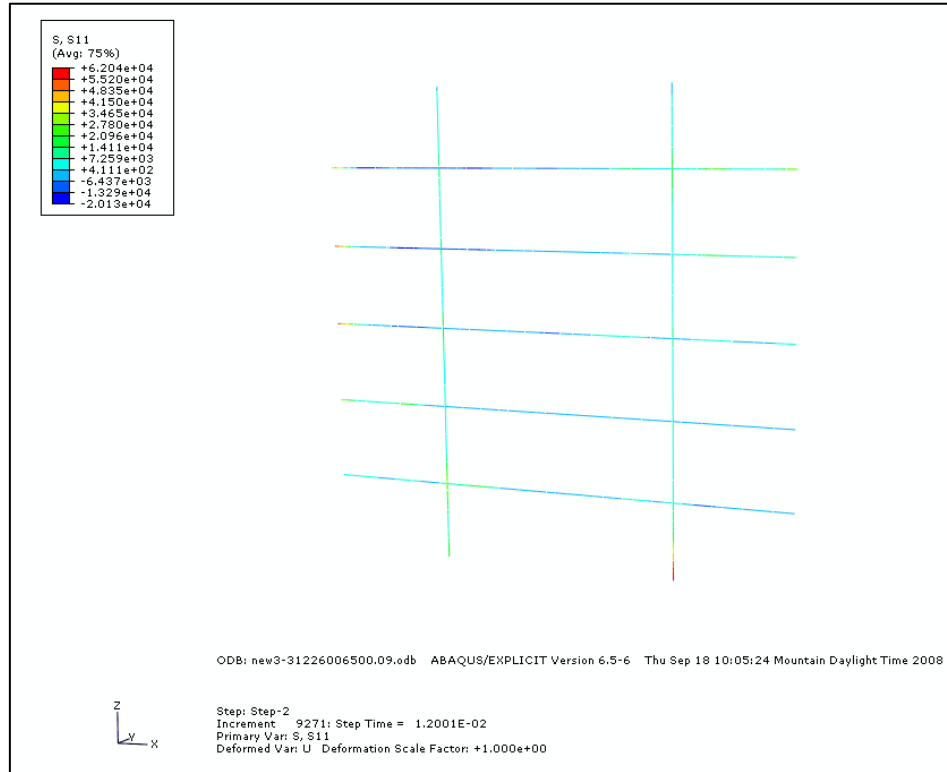


Figure 22. Rebar and wires stress distribution (in psi) – fixed Arquin wall

The Dual Wall Concept

In addition to the single wall described in this report, The Arquin Corporation also has a dual wall design concept. This concept also uses the steel wire and polymer spacers. The dual wall concept is illustrated in Figure 23. Note that in this concept, one of the steel wires connects the two walls. The space between the walls could be filled with a variety of material to achieve desired wall properties. Note that this wall concept was not analyzed under this effort. However, based on the improved performance observed with the single wall design, it is reasonable to conclude that the Arquin dual wall concept will also perform very well against dynamic loads.

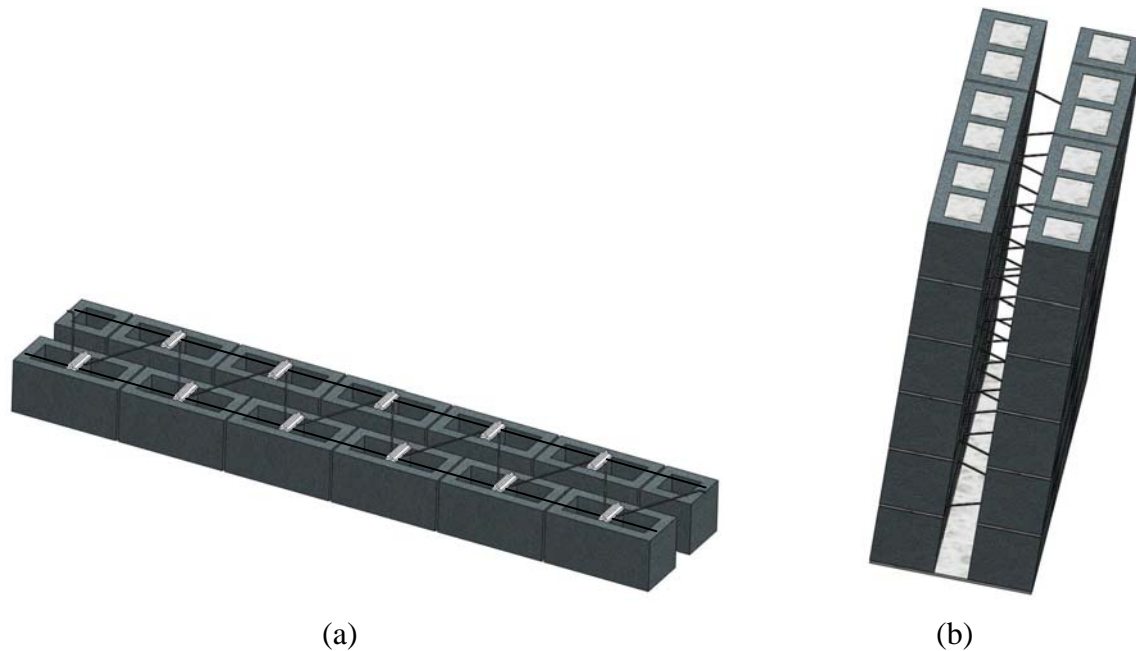


Figure 23. Arquin dual wall design; (a) first course of CMUs and one of the possible “V-shaped” wire design concepts; (b) “V-shaped” wire tying two CMU walls

Summary

The results presented in this report show that the Arquin wall is capable of withstanding a blast-like dynamic load (30psi in 0.01 seconds) with less deformation than the idealized standard reinforced wall analyzed. The load applied to the idealized standard wall and the Arquin wall (8ft. long by 4ft. high) is equivalent to 138,240 pounds distributed over one side of the wall and applied over one-hundredth of a second. It is important to note that the Arquin wall has all cells filled with concrete instead of every third cell filled in the idealized standard wall. This difference alone will lead to a stronger wall.

It is very important to emphasize that, while not quantified as part of this effort, there is a level of uncertainty in the reported values of stress and displacements for each of the walls analyzed. Therefore, the use absolute values or results to calculate exact differences between the cases that were analyzed would be an improper use of these data. Nevertheless, the results from the analyses show that the Arquin wall deformed less than the idealized standard reinforced wall analyzed, given the assumptions and conditions used in this study.

In a case where a more localized load is applied, the Arquin wall may perform better than the idealized standard wall if the load is applied in regions where the idealized standard wall does not have a rebar to take the load. Therefore, if the Arquin wall concept enables a builder to raise a wall at a fraction of the time it normally takes when employing other techniques, the wall building technique proposed by The Arquin Corporation is an option to be considered by the construction industry.

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Ho, C.K., T.A. Bibeau, and A. Quinones, Sr., *Finite Element Analysis of Continuous Filament Ties for Masonry Applications: Final Report for the Arquin Corporation*, SAND2008-5518, Sandia National Laboratories, Albuquerque, NM, August 2008.

Analysis User's Manual, Abaqus Version 6.5, Abaqus Inc., Providence, RI.

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